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Key Points:
- The state of the atmosphere is observed to vary naturally on all time scales from seconds to decades and longer
- This paper synthesizes and summarizes that variability through a phenomenological census
- The paper provides an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability

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A Census of Atmospheric Variability From Seconds to Decades

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Abstract This paper synthesizes and summarizes atmospheric variability on time scales from seconds to decades through a phenomenological census. We focus mainly on unforced variability in the troposphere, stratosphere, and mesosphere. In addition to atmosphere-only modes, our scope also includes coupled modes, in which the atmosphere interacts with the other components of the Earth system, such as the ocean, hydrosphere, and cryosphere. The topics covered include turbulence on time scales of seconds and minutes, gravity waves on time scales of hours, weather systems on time scales of days, atmospheric blocking on time scales of weeks, the Madden–Julian Oscillation on time scales of months, the Quasi-Biennial Oscillation and El Niño–Southern Oscillation on time scales of years, and the North Atlantic, Arctic, Antarctic, Pacific Decadal, and Atlantic Multidecadal Oscillations on time scales of decades. The paper serves as an introduction to a special collection of *Geophysical Research Letters* on atmospheric variability. We hope that both this paper and the collection will serve as a useful resource for the atmospheric science community and will act as inspiration for setting future research directions.

1. Introduction

The state of the atmosphere is observed to vary naturally on all length scales from the Kolmogorov dissipation scale of millimeters up to the planetary scale of thousands of kilometers, and on all time scales from seconds to decades and longer. This Commentary synthesizes and summarizes that variability through a phenomenological census. The focus of the Commentary is necessarily restricted, not least because we have to get from seconds to decades within the space of only a few pages! Therefore, we focus mainly on unforced variability in the troposphere, stratosphere, and mesosphere. Our scope includes coupled modes, in which the atmosphere interacts with the other components of the Earth system, such as the ocean, hydrosphere, and cryosphere. Given these interactions, and the importance of the atmosphere for weather and climate, our intended audience is the entire *Geophysical Research Letters* readership. Our aim is to provide an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability.

This Commentary serves as an introductory foreword to a virtual special collection of *Geophysical Research Letters* on atmospheric variability. To initiate the collection, we have identified some of the most influential and definitive papers to have been published in this journal in recent years. Our hope and expectation is that this will be a living collection, which will grow over time whenever seminal new papers are published.

The contents of the Commentary are ordered in terms of increasing time scale, from seconds and minutes (section 2), to hours (section 3), days (section 4), weeks (section 5), months (section 6), years (section 7), and decades (section 8). We note at the outset, however, that the time scales of many atmospheric phenomena are not unambiguously defined. For example, the Madden–Julian Oscillation (section 6) is monitored and forecasted from week to week but its spectral peak is 30–90 days, and a typical El Niño–Southern Oscillation event (section 7) has a duration of seasons but its spectral peak is 2–7 years. Therefore, while some phenomena are most easily identified in data spanning longer periods, their impacts may be experienced on considerably shorter time scales.

2. Seconds and Minutes: Turbulence

Atmospheric turbulence is an important component of dynamical variability on time scales of less than a few minutes. The atmospheric boundary layer, which is the lowest part of the atmosphere, mediates the vertical transport of heat, moisture, and momentum between Earth's surface and the free atmosphere. The rapid diurnal cycle of the boundary layer generates turbulence, which makes the boundary layer and its clouds challenging to represent in numerical weather prediction models and global climate models (Bony et al., 2015; Holtslag et al., 2013; Pithan et al., 2015). The challenges associated with boundary layer turbulence have implications for weather forecasting, assessment of regional climate variability (Ludwig et al., 2017), and climate change mitigation (Rigden & Li, 2017). Rapid atmospheric turbulence at the air–sea interface may have significant climatic impacts because of nonlinearities in the ocean's response to atmospheric forcing (Williams, 2012). At short spatiotemporal scales, large-eddy simulations may be used to assess the atmospheric boundary layer's impacts on clouds (Chu et al., 2014), pollution transport (Cécé et al., 2016), wildfires (Coen et al., 2012), and renewable energy (Worsnop et al., 2017). Dynamic downscaling of mesoscale simulations to large-eddy simulations incorporates mesoscale variability while introducing challenges when parameterized atmospheric boundary layer turbulence interacts with directly represented turbulence (Shin & Dudhia, 2016). Recent progress in coupling large-eddy simulations and weather models is promising (Muñoz–Esparza et al., 2017).

Above the atmospheric boundary layer, in the upper troposphere and lower stratosphere, turbulence affects aviation and contributes to stratosphere–troposphere exchange of atmospheric constituents. Although the importance of Kelvin–Helmholtz instability for clear-air turbulence is accepted (e.g., Dutton & Panofsky, 1970; Whiteway et al., 2004), interactions between wind shear and gravity waves (see section 3) have emerged as an important clear-air turbulence generation process (e.g., Knox et al., 2008; Pavelin et al., 2002; Sharman et al., 2012). Convective clouds are also an important source of turbulence. The spatial patterns of thunderstorm-generated turbulence have been exposed by high-resolution simulations (Lane & Sharman, 2014), with gravity wave breaking identified as an important mechanism (Lane et al., 2012). Moreover, new observations and mesoscale models have shown that turbulence often extends well beyond a thunderstorm's convective region, caused by Kelvin–Helmholtz instability in upper outflow regions (Trier & Sharman, 2009) and by gravity wave breaking above storms (Trier et al., 2012).

3. Hours: Gravity Waves

With oscillations centered on time scales of hours but ranging from minutes to days and spanning the mesoscale, gravity wave variability lies at the heart of many current research foci. In particular, gravity waves span the range of resolutions in current global models developed for weather forecasting (~10 km) and climate prediction (~100 km). In these models, gravity wave drag controls wind biases that affect synoptic weather and climate patterns of variability (Alexander et al., 2010; Plougonven & Zhang, 2014). However, even at resolutions of around 10 km, global models severely under-resolve the gravity wave spectrum (Holt et al., 2016; Jewtoukoff et al., 2015) and their drag effects are still parameterized. Observing these waves stretches the limits of global observing systems (Alexander, 2015; Geller et al., 2013). In the tropics, gravity waves may influence the Madden–Julian Oscillation (Yang & Ingersoll, 2014; see section 6). At high latitudes, gravity waves affect polar temperatures and ozone loss (Eckermann et al., 2009), and localized wave sources that generate large-amplitude waves are key to simulating realistic climate (de la Cámara & Lott, 2015). Whether jet stream imbalance is an important gravity wave source remains unclear (Williams et al., 2005, 2008). Resolving the gravity wave sources and the breaking process remains a challenge for even the highest-resolution models (Lane & Sharman, 2006; Fritts, Wang, et al., 2016). Poorly resolved short vertical wavelength waves (sometimes with very large horizontal scales) modulate tropopause temperatures, ozone, and tropical cirrus (Pierce & Grant, 1998; Jensen et al., 1996; J.-E. Kim et al., 2016). Thus, atmospheric gravity waves impact atmospheric variability on spatial scales ranging from the global to the microscale.

Above the troposphere and stratosphere, momentum deposition by gravity waves affects the zonal-mean wind, temperature, and meridional circulation in the mesosphere (Fritts & Alexander, 2003; Holton, 1983; Matsuno, 1982). Simulations using recently developed gravity wave-permitting general circulation models indicate that gravity waves emitted from tropospheric sources such as topography, convection, and jet-front systems may propagate large distances horizontally before reaching the mesosphere (Liu et al., 2014; Sato et al., 2009). Quantitative observational studies of momentum fluxes and wave characteristics have been performed using state-of-the-art instruments (Chu et al., 2011) and by combining multiple instruments (Alexander, 2015; Fritts, Smith, et al., 2016). Other important gravity wave phenomena include vertical coupling associated with an elevated stratopause (Chandran et al., 2011; Manney et al., 2009; Tomikawa et al., 2012) and interhemispheric coupling initiated by Sudden Stratospheric Warming events that may modify gravity wave propagation (Karlsson et al., 2009; Körnich & Becker, 2010).

4. Days: Weather Systems

In the extratropics, synoptic-scale weather systems drive atmospheric variability on time scales from days to weeks. Extratropical cyclones feature weather fronts, strong surface pressure variations, and rapidly ascending airstreams (Catto, 2016). They can produce strong surface winds (Ulbrich et al., 2001), heavy precipitation (Pfahl et al., 2014), and intense convection (Schemm et al., 2017). Quasi-stationary anticyclones, which are also known as atmospheric blocks (see section 5), can lead to prolonged dry and cold conditions in winter (Buehler et al., 2011) and dry and hot conditions in summer (Black et al., 2004). The movement of weather systems (and therefore the occurrence of weather extremes) is steered by the large-scale flow (Rothlisberger et al., 2016). However, the large-scale flow is also strongly affected by the weather systems (Yamada & Pauluis, 2017). In particular, weather systems resulting in surface extremes can exert a very strong feedback on the large-scale flow and low-frequency variability (Riviere & Orlanski, 2007) such as the North Atlantic Oscillation and its teleconnections (see sections 7 and 8). They can also move the flow into or out of a state in which weather extremes occur in one particular location (Hanley & Caballero, 2012).

In the tropics, the modulation of global cyclone activity as observed during the past 50 years is exemplified by low-frequency, intraseasonal to interannual oscillatory variability including the Madden–Julian Oscillation (Maloney & Hartmann, 2000), El Niño–Southern Oscillation (Camargo & Sobel, 2005), Pacific Decadal Oscillation (Chan, 2008), and Atlantic Multidecadal Oscillation (Bell & Chelliah, 2006; Gray, 1984). On average, 87 ± 8 named tropical cyclones ($>$34 knots or 17 m s^{-1}) occur annually, of which 47 ± 7 reach hurricane strength ($>$64 knots or 33 m s^{-1}), and they are distributed unevenly among the active Pacific, Indian, and Atlantic Ocean basins (Klotzbach & Landsea, 2015). Integrated activity metrics such as the Accumulated Cyclone Energy have fluctuated considerably over the past three decades, closely related to modes of global climate variability (Maue, 2011). Climate modeling studies suggest that global tropical cyclone numbers are predictable on seasonal to decadal timescales (Smith et al., 2010; Vecchi et al., 2014) and may see a slight increase in intensity against a decrease in frequency by 2100 due to global warming (Knutson et al., 2010).

5. Weeks: Atmospheric Blocking

An atmospheric block is a weather regime comprising a quasi-stationary region of high pressure that disrupts the extratropical westerly storm tracks, persists for around a week or longer, and possesses a horizontal half-width of a thousand or more kilometers. The airflow around the block is anticyclonic and Ω-shaped. Many of the weather extremes that impact the midlatitudes are associated with atmospheric blocks, such as heat waves (Dole et al., 2011), cold spells (Cattiaux et al., 2010), poor air quality (Fowler et al., 2008), and even Superstorm Sandy (Barnes et al., 2013). Blocks occur most frequently over the Pacific and Atlantic oceans and result from Rossby-wave breaking and the emergence of a low potential vorticity pool in the upper troposphere (Pelly & Hoskins, 2003; Schwierz et al., 2004). Blocks are precursors of, and linked to, the North Atlantic Oscillation and the Eastern Atlantic and Pacific-North America patterns of interannual climate variability (Croci–Maspoli et al., 2007a; Woollings et al., 2010; see section 8) and the occurrence of Sudden Stratospheric Warming events (Martius et al., 2009). Blocks often contribute substantially to seasonal anomaly patterns, and therefore they need to be captured adequately in weather and climate models (Dole et al., 2011; Matsueda, 2011; Scaife et al., 2011).

Recent and future climatological trends in blocking are of considerable interest (Croci–Maspoli et al., 2007b, Sillmann & Croci–Maspoli, 2009) because anthropogenic climate change is expected to cause significant changes in climate and weather extremes (Seneviratne et al., 2012). While it is well known that variations in blocking frequency are tightly tied to variations in the midlatitude jet streams and storm tracks (Berrisford et al., 2007), the extent to which these relationships explain the response of blocking to climate warming is unclear (Hassanzadeh & Kuang, 2015). Part of the confusion is due to disagreement about whether we have already witnessed changes in blocking over the satellite record. For example, some studies suggest that the recent decline of Arctic sea ice and associated Arctic warming have driven increases in blocking frequency throughout the northern midlatitudes (Francis & Vavrus, 2012; Liu et al., 2012). On the other hand, Barnes et al. (2014) compared regional trends in three unique blocking data sets and four different reanalysis products and concluded that no robust hemispheric trends in blocking have been observed. Furthermore, causal links between future Arctic warming and increasing blocking frequencies have been challenged in the literature (Hassanzadeh et al., 2014; Woollings et al., 2014). The extensive and dichotomous scientific debate about blocking trends in the present and coming decades highlights the difficulty of identifying forced trends in blocking from a background of substantial internally driven interannual and decadal variability.

6. Months: The Madden–Julian Oscillation

The Madden–Julian Oscillation (MJO) is an atmospheric phenomenon in the tropics with dominant timescales of 30–90 days (Madden & Julian, 1971, 1972). It features eastward propagation of large-scale patterns of rainfall, zonal wind, and humidity at an average speed of 5 m s^{-1} along the equator from the Indian Ocean to the Pacific Ocean (Zhang, 2005). Tremendous progress has been made in the study of the MJO during the past four decades (Zhang et al., 2013) and recently in its understanding (Ma & Kuang, 2016; Xu & Rutledge, 2016; Yang & Ingersoll, 2014), simulation (Ajayamohan et al., 2013; Ling et al., 2017; Song & Seo, 2016), and prediction (Chen et al., 2014; Shelly et al., 2014). Because of its timescale and expected eastward propagation, the MJO is considered to be a major source of predictability on subseasonal to seasonal timescales (Vitart, 2017; Waliser et al., 2003).

In the tropics, the MJO influences higher-frequency phenomena such as tropical cyclones (see section 4) and lower-frequency phenomena such as El Niño (see section 7). The tropical diabatic heating associated with the MJO excites subtropical planetary waves via its divergent outflow, and these subtropical Rossby waves then propagate poleward and impact the extratropical Pacific and Indian Ocean sectors (Bao & Hartmann, 2014; Seo & Son, 2012) including populated regions of Asia and North America (Higgins et al., 2000; Zhang, 2013). These wave perturbations can then influence hemispherically symmetric weather patterns in the extratropics of both the Southern (Matthews & Meredith, 2004) and Northern Hemispheres (L'Heureux & Higgins, 2008; Riddle et al., 2013) and modulate the North Atlantic Oscillation (Lin et al., 2009). The MJO has also been linked to changes in individual cyclones and blocking events (Guo et al., 2017; Henderson et al., 2016). These linkages influence the distribution of climate extremes (Hoell et al., 2014; Zhang, 2013), and they also impact the stratosphere (Garfinkel et al., 2012; Garfinkel et al., 2014).

7. Years: The Quasi-Biennial Oscillation and El Niño–Southern Oscillation

Seasonal-to-decadal forecasts of the three-dimensional state of the atmosphere are routinely produced using general circulation models (GCMs) initialized with observations and integrated forward months or years ahead. Coupled modes involving the slowly varying tropical ocean provide predictability, some of which leaks into the extratropics where it drives potentially useful predictions (Scaife, Arribas, et al., 2014). The Quasi-Biennial Oscillation (QBO) is a notable exception to this ocean-dominated picture. The QBO is a purely internal atmospheric phenomenon, which has period of around 28 months. It is driven by momentum fluxes from vertically propagating internal waves (Geller et al., 2013) and is now reproduced in GCMs (Giorgetta et al., 2002; Scaife et al., 2000). Much less well studied is its predictability. Scaife, Athanassiadou, et al. (2014) showed that the QBO can be skillfully predicted out to several years. However, this predictability does not extend to the QBO's modeled surface impacts (Baldwin et al., 2001; Ebdon, 1975). The prediction systems analyzed by Scaife, Athanassiadou, et al. (2014) showed only a weak version of the observed surface signal.

This may be part of a wider issue (Eade et al., 2014) and could provide additional skill in future improved prediction systems.

The El Niño–Southern Oscillation (ENSO) is a coupling between the tropical atmosphere and ocean on timescales of roughly 2–7 years, with societal and economic impacts spanning the globe (Arblaster & Alexander, 2012; Greatbatch et al., 2004; Hoell et al., 2016; Klotzbach, 2011; Lyon, 2004; Zeng & Pyle, 2005). During the El Niño phase of ENSO, a relaxation of the tropical trade winds flattens the oceanic thermocline, reducing upwelling of cold deep water and driving anomalously warm sea surface temperatures (SSTs) in the eastern tropical Pacific. Conversely, anomalously cool SSTs in the eastern Pacific form during the La Niña phase. Shifts in the region of warm SSTs modify convective patterns, driving remote changes to the global atmospheric circulation via both tropospheric and stratospheric pathways (Butler & Polvani, 2011; Iza & Calvo, 2015; Trenberth et al., 1998). Because ENSO explains a nontrivial fraction of midlatitude atmospheric variability (Seager et al., 2003), it is an important predictor in seasonal climate forecasts (Ropelewski & Halpert, 1987), despite the diversity of ENSO events (Capotondi et al., 2015) and the difficulty of isolating the ENSO signal from large internal atmospheric variability (Deser et al., 2017). Predicting the phase and amplitude of ENSO itself also remains challenging for certain seasons and lead times (Barnston et al., 2017; Levine & McPhaden, 2015; Martín-Rey et al., 2015; McPhaden et al., 2006; Wang et al., 2011).

8. Decades: The North Atlantic, Arctic, Antarctic, Pacific Decadal, and Atlantic Multidecadal Oscillations

The North Atlantic Oscillation (NAO) is a perturbation of the atmospheric circulation over the North Atlantic Ocean. It is a north–south seesaw in atmospheric mass, simultaneously affecting the strengths of the surface Icelandic low and Azores high (Hurrell et al., 2003; Wanner et al., 2001). While the nominal persistence of the perturbation is measured in days, the NAO exhibits variability on a broad range of time scales including interannual and decadal. The NAO is expressed through the depth of the troposphere by a pressure dipole, straddling the mean latitude of the jet stream (Kushnir & Wallace, 1989). In that respect, the NAO resembles the Arctic Oscillation, which has an additional footprint in the North Pacific and emphasizes a deep extension into the stratosphere (Deser, 2000; Wallace, 2000). The analogous mode in the Southern Hemisphere is the Antarctic Oscillation or Southern Annular Mode, which is an important driver of rainfall variability in southern Australia (Gong & Wang, 1999; Meneghini et al., 2007). Geostrophy implies that the NAO is also a simultaneous perturbation in the latitudinal position and strength of the North Atlantic jet stream. The north–south swings interact with the parallel movement of the extratropical storm track (Riviere & Orlanski, 2007). The NAO changes the surface wind strength and direction, thereby forcing changes in the ocean (Dickson et al., 2000; Eden & Jung, 2001; Kwok, 2000; Visbeck et al., 1998). Because of its considerable climatic impacts, many attempts have been made to predict the winter NAO using statistical methods (Cohen & Entekhabi, 1999) and general circulation models (Scaife, Arribas, et al., 2014). The societal benefits of skillful predictions could be large (Smith et al., 2016).

The Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and the Atlantic Multi-decadal Oscillation (AMO) (Kerr, 2000) are defined in terms of sea surface temperature variability in the northern portions of these individual basins. Their existence relies upon dynamical coupling between the atmosphere and the ocean. Empirical orthogonal function analyses of appropriately filtered sea surface temperature data for the Pacific Ocean north of 20°N (d'Orgeville & Peltier, 2007) demonstrate the PDO to consist of two primary components with characteristic periods of around 20 years and 60 years. The lower-frequency component simply modulates the amplitude of the higher-frequency component. The higher-frequency component is interpreted as a basin-scale mode governed by westward propagating Rossby wave dynamics within the ocean (Latif and Barnett, 1996; Cessi & Louazel, 2001). Models are highly successful in capturing the PDO (d'Orgeville & Peltier, 2009a), although the predictability may be low (see Newman et al., 2016, for a recent discussion). The AMO, on the other hand, has a characteristic period of around 60 years and is strongly connected to variability in the strength of the Atlantic Meridional Overturning Circulation. Models have generally been found to have difficulty in capturing the observed 60 year period of this mode (but see d'Orgeville & Peltier, 2009b). d'Orgeville and Peltier (2007) demonstrate that the 60 year modulation of the amplitude of the PDO is simply a phase-lagged version of the AMO, suggesting that these northern hemisphere modes of coupled ocean–atmosphere dynamics may be deeply connected.

9. Summary

This Commentary has attempted to provide an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability. We make no claims that our coverage of the subject matter has been comprehensive, and the astute reader will certainly find gaps. For example, we have largely neglected interactions between the modes, such as the known dependence of turbulence on the North Atlantic Oscillation (J.-H. Kim et al., 2016). With one or two exceptions, we have also largely neglected the forced component of variability, which originates from anthropogenic interference, volcanic activity, and solar variability. For example, some aspects of the variability may be modified by anthropogenic climate change, such as the hypothesized future increase in turbulence induced by changes to the jet stream (Storer et al., 2017; Williams, 2017; Williams & Joshi, 2013). Finally, we have hardly touched on the problem of how to parameterize the impacts of the subgrid-scale variability on the resolved flow in numerical models, or the question of whether simulations will be improved by increased model resolution. Nevertheless, we hope that the Commentary will serve as a useful resource for the atmospheric science community and that the papers contained within the special collection will act as inspiration for setting future research directions.

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